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RF Voltage Breakdown in Coaxial Transmission Lines

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With increasing RF power requirements for space missions, RF voltage breakdown has received considerable attention. Of particular interest is the coaxial transmission line configuration, since it is often encountered in the RF system. When pressure is sufficiently low that the mean free path is longer than the inner-to-outer conductor separation distance d , multipacting can occur. Multipacting breakdown in the coaxial line geometry has been investigated previously (Refs. 1 and 2). As pressure is increased, the mean free path is shortened. When the mean free path becomes shorter than the separation distance, the principal electron production mechanism is no longer secondary electron emission, but ionization by electron collision. Breakdown that occurs under these conditions will be termed ionization breakdown. There have been studies of ionization breakdown in the coaxial line geometry, but these have generally been restricted in terms of experimental parameters and breakdown processes (Refs. 3-5). Moreover, these breakdown data have been displayed in rather complex and impractical schemes. We have obtained a large amount

of breakdown data in air for the $50\ \Omega$ coaxial line geometry, and the data are summarized in a unified, concise, and practical plot.

Two experimental setups were used: (1) 10-150 MHz lumped circuit test set (Ref. 1), and (2) 150-800 MHz and 1700-2400 MHz transmission line test set (Ref. 2). Dry air was used and pressure was measured with a McLeod's gage. To minimize the effects of products of ionization of one breakdown measurement on subsequent breakdown measurements, the vacuum system was evacuated to less than $30\ \mu$ and new air introduced before each breakdown measurement. Reproducibility of the breakdown power readings was within $\pm 4\%$, and the accuracy of the readings was within $\pm 4\%$.

Figure 1 summarizes the data obtained; p is the pressure, f is the frequency of the applied field, and λ is the wavelength of the applied field. Multipacting breakdown data corresponding to the lower breakdown boundary and obtained previously have been included along

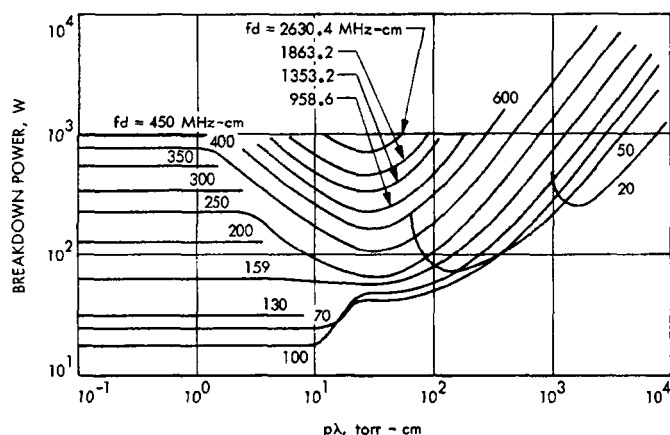


Fig. 1. Unified plot for RF voltage breakdown in 50-Ω coaxial transmission lines

with the ionization breakdown data. Brown and MacDonald (Ref. 6) showed that breakdown data can be represented by a three-dimensional surface using similarity parameters. Figure 1 essentially defines this surface. However, the similarity parameters of Fig. 1 are not the same as those used by Brown and MacDonald, but have been chosen for practical reasons. If a design engineer wishes to determine the breakdown behavior of a coaxial transmission line component at a particular frequency, he computes the corresponding fd . By referring to Fig. 1 he not only has breakdown power as a function of pressure, but also information on the effects of changing either frequency or line size.

The fd - $p\lambda$ plane shown in Fig. 2 is very helpful in identifying the breakdown processes involved. The limits indicated are similar to those discussed by Brown and

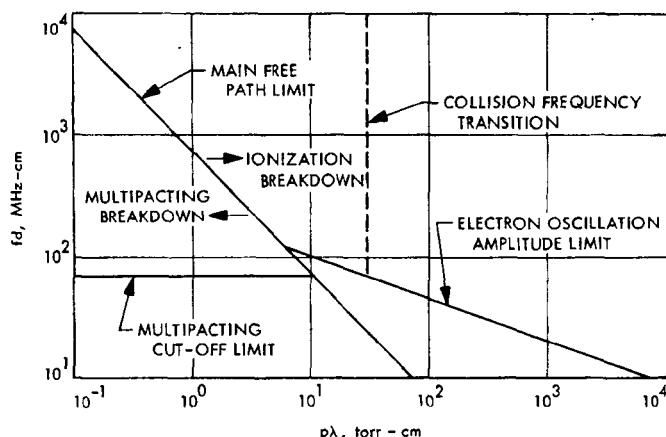


Fig. 2. The fd - $p\lambda$ plane showing limits of breakdown processes

MacDonald (Refs. 6-8). Although they are in the form of lines they are meant to indicate transition rather than abrupt change. The mean free path limit separates the ionization and multipacting breakdown regions. For fd values less than the multipacting cutoff limit, multipacting will not occur.

It is also convenient to use the similarity parameter fd in discussing the ionization breakdown region. When fd is greater than approximately 100 MHz-cm, frequency is sufficiently high and the separation distance sufficiently large that the electrons are not swept out of the discharge region. This is diffusion-controlled breakdown. The minimum breakdown power occurs at the collision frequency transition ($p\lambda \sim 30$ torr-cm). The electron neutral collision frequency and the applied frequency are approximately equal at the collision frequency transition, and energy transfer to the electrons from the field is maximum. When fd is less than 100 MHz-cm, the applied frequency is sufficiently low and the separation distance sufficiently short that the amplitude of oscillation of the electron cloud can approach and exceed the separation distance. The oscillation amplitude limit corresponds to the condition for which the amplitude of oscillation of the electron cloud is equal to the separation distance. At this limit, electrons are lost to the conductor surfaces, and the power required for breakdown rises rapidly. This behavior is illustrated in Fig. 1 for fd values of 50 and 20 MHz-cm. In the case of $fd = 20$ MHz-cm, another minimum is observed if pressure is further decreased. This additional minimum is present for smaller values of fd as well. This region has been studied by Gill and von Engel (Ref. 9) who attribute the additional minimum to the ions.

The scaling correspondence for ionization breakdown was checked between various sets of data. Frequency was changed as much as seven times. Scaling correspondence was within reproducibility of the data except for the region around $fd = 100$ MHz-cm between $p\lambda$ values of 10 and 100 torr-cm. In this region the spread in the data was as much as 30 W and breakdown power increased with a decrease in separation distance when fd was held constant. This is to be expected since as discussed above this is a region of several transitions and breakdown is affected by surface conditions.

The minimum power-handling capability is of particular interest. Shown in Fig. 3 is breakdown power as a function of fd along the collision frequency transition. This gives the minima of the diffusion-controlled break-

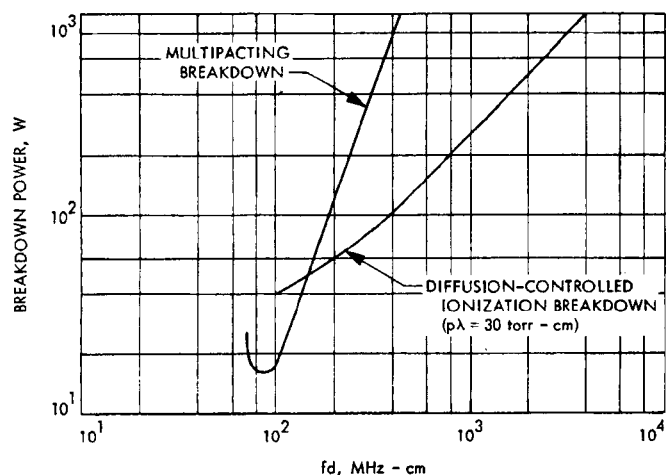


Fig. 3. Minimum power-handling capability in terms of fd

down curves. The multipacting data are also included for comparison. When fd is less than 145 MHz-cm, the ionization breakdown power level is higher than the multipacting breakdown power level; the reverse is true when fd is greater than 145 MHz-cm.

It should be emphasized that the data of Fig. 1 correspond to a perfectly matched transmission line. If mismatches in the line exist, the breakdown power level must be correspondingly derated. The scheme of data presentation in Fig. 1 can be used for configurations other than the 50 Ω coaxial line. Similar curves can also be obtained for gases other than air.

I should like to express my gratitude to G. Voyles of the Jet Propulsion Laboratory for his efforts in obtaining the experimental data.

Discussion

Woo: I just remembered that there is an important point I forgot to make. With reference to the curves that I showed you for RF, you can also see what happens as you gradually decrease frequency as you go from microwave into the audio regions, because you can extend it.

Furthermore, you can extrapolate on the high pressure side and come up with curves good at atmospheric pressures for the coaxial transmission line geometry. We have done that.

August: I think that was very good, and the information is presented in, I think, a rather useful way for design engineers. The only point I would like to comment on is, and this is not a criticism, but I think you have to emphasize other things besides just plain mismatch.

First off, there are essentially universal curves for computing what the breakdown levels are from which you basically get your design curves, so that in cases where you run into odd geometries at coaxial connectors or at windows or other things, I think you have to get off these things and go to the universal curves from which you derive these.

However, I am glad you emphasized the aspect of mismatch. One thing you have to worry about besides mismatch is that you can essentially derate those curves by 6 dB and double the field at 100% mismatch. This will establish a minimum level. This is fine except perhaps where you are feeding through a transmitter, where you have very high reactive fields which are in excess of double the level you would assume on the transmission line from power transmission aspects. This also applies to irises or other obstructions where you have high reactive fields, which you can't get by, let's say, by doubling the assumed voltage level on the transmission line. In those cases you have to get off these things and go back to the universal curves.

I guess you assumed either copper or aluminum for establishing your multipacting curves and variation with respect to the ionization curves. This would usually be true for most things so that these curves are usable.

Again, in design manuals I think you need to emphasize the point that if you get off these things, you better be careful, because you can shift the multipacting level up and down in relation to the minimum of ionization.

One further thing that I think is sometimes ignored in putting these things together in systems is that the ionization levels and also the multipacting levels are affected by stray magnetic fields that you may get from other components, so that if you have these close to your transmission lines you better do something else.

Woo: Those are good comments. You were talking about irises and things like that. This is basically for the coaxial transmission line geometry. In relation to space missions, most of the lines are very well matched, so this study applies to those conditions.

August: The important thing there is that I think we have usually found that our problems tend to be right at the window feed through, from whatever your transmission line transmitter is in a coaxial line or in a wave guide system, because then you have the reactive field. Even if you are well matched, you always have reactive fields.

There again, you perhaps have to take the diffusion losses to, let's say, supports for the coaxial line or for the wave guide, whatever it may be.

Woo: This transmission line is just one part of the whole system.

Young: On your coaxial transmission lines, have you performed any shielding effect tests or RF leakage tests at sea level and at the

Discussion (contd)

critical air pressure, for comparative purposes? If so, what were your observations?

Woo: Are you talking about the microwave transmission line system setup?

Young: I am more interested in the typical coaxial transmission lines.

Woo: I see. Well, the lines are terminated and there is no leakage in the system.

Are you asking if when you hook up the transmission line components is there any leakage?

Young: You would normally have some leakage.

Woo: I see. No, we didn't measure that. I don't think there was much leakage because it was a pretty tight system. Are you asking us because of safety hazards or --

Young: Suppose you have standing waves, for example, on lines have been known to cause certain voltage breakdown problems. In a number of papers that have been presented, there have been remarks of a sudden increase in the VSWR under certain conditions. I believe this is probably brought about by a change in the

characteristic impedance of the line. You are suddenly no longer terminated in the characteristic impedance in the line; therefore, you get an increase in the VSWR which can cause breakdown.

Woo: Well, we just tested for the initiating conditions. As soon as it breaks down we turn it off. When the breakdown does occur, the power is reflected; we have a circulator and it dumps the power into a dummy load.

Young: I guess your tests are not typical shielding effectiveness tests.

Woo: No, I guess not.

August: One more comment about the multipacting breakdown. We put out these curves and we do this design information mostly because we are concerned that if we do get a breakdown it might ruin the characteristics of the system. I think it is important to point out that under many conditions, multipacting is not a really significant parameter in that you can allow a system to multipact and you may lose a little power, assuming that you have outgassed it and taken care of all the transient problems that develop, and you can allow a system to multipact, so that the multipacting limits that you show are merely for onset and not necessarily where the system is being damaged particularly by the multipacting.

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